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退化草地生态恢复研究案例综合分析:年限、效果和方法

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摘要:草地生态系统退化严重影响着全球生态安全、草原区域居民生计和草原文化多样性的发展。退化草地恢复工作依赖于对有效研究案例的借鉴,不同研究年限的案例对生态恢复实践的目标、恢复方案的制定有不同借鉴和参考作用,而获得有指导价值的研究案例通常是长期开展的研究工作。在调查国内外 149 个退化草地生态恢复案例基础上,该文综合分析了退化草地生态恢复的研究年限分布、恢复目标、恢复方法,效果及长期研究数据获取方法等,主要有以下几方面总结。(1)年限小于 10a 的案例数量较多,且更侧重于连续性研究;较长时间研究更多依赖于以前研究案例重访性研究。(2)相对而言,较长期的研究结果可靠性更高,其恢复技术的说服性更强,对于生产力的研究一般比生态功能研究的案例年限短些。(3)在退化草地生态恢复中,恢复目标排在前三位的分别是生物多样性,植被覆盖度和土壤碳库。(4)在调查的研究案例中关于动物群落的研究非常少。(5)退化草地恢复方法中应用最多是人工播种,围栏封育,放牧应用。(6)跨度时间较长的研究工作大多采用案例重访的方式,获取和以前可对比的数据资料。最后,建议特别应该重视案例重访方法的应用,尽可能更多的开展实地性数据获取再进行大数据综合,这样更可靠。

关键词:退化草地;生态恢复;研究年限;恢复效果;案例重访;'分散协作-方法统一'

Synthesis-review for research cases of grassland ecological restoration: Years, effect and method

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Abstract: The degradation and deterioration of grassland ecosystem had influenced the global ecological security, local resident livelihood and development of culture diversity in rangeland area. The restoration projects successful depend on the good experience provided by effective study case, and then those cases normally are with different study years. And the study case with different years have different indicators or guidelines for the restoration goal, method. Moreover, the long-

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term in the grassland restoration study is seen very important for getting more experience. This paper had reviewed 149 international study cases of grassland restoration with different study period, and analysis the study time pattern, restoring goal, restoring method, and restoration effect, and the long-term data getting method etc, and we had several summary points in the following context. (1) In the 149 cases, the most cases were less 10 years, that focus on continuous experiment every years, and on the other hand, the long-term study cases (>10 years) rely on the filed revisiting. (2) The study with long-term monitoring and survey has more reliability in the results, and have more useful guideline of restoration technique. In normal, the study objective with the productivity had less study period (years) than that with the objective of ecological function. (3) In those study cases, three most restoration goals were biodiversity, vegetation coverage, and soil carbon pool. (4) There were few cases about animal community. (5) The most restoration method or approach applied in the study were seed sowing, fencing exclusion, and grazing. (6) The study with longer time (years) in the grassland restoration applied the method of field revisiting to get the data from same filed sites could be compared with previous records. As the conclusion, the authors suggested that we should pay attention to the application of field revisiting method in monitoring and evaluation of grassland restoration's effect. We should conduct more and more the on-site field measurement and then do the data analysis, and big-data synthesis then their result will be more effective.

Key Words: grassland degradation; ecological restoration; study period (years); restoration effect; field case revisiting; Coordinated distributed experiments-uniformed methods

在过去的一个世纪,全球草地生态系统经历着有人类以来最为严重的威胁。这种威胁导致了大范围和多形式的草地退化,其退化的结果包括生物多样性丧失、生态系统功能减弱、当地赖以生存的居民生计减少或沦为难民。近 50a 来,发展中国家步入生产高速发展的阶段,草地生态系统亦趋工业化毁坏之后尘[1-3]。大范围的草地荒漠化、毒杂草化等等,都在更严峻威胁着占全球陆地面积 25%的草原。例如,从本世纪初到现在,中国媒体一直宣称中国有 90%的草原处于退化状态[4]。因此,全球退化草地生态恢复面临着提高其生计维持功能、生态服务功能的巨大挑战。

生态学家,特别是恢复生态学家长期以来一直关注退化草地生态系统的恢复,并致力于研究和实践工作[5-7]。研究案例的年限与恢复效果,方法有效性有着紧密的联系,对实践的指导价值也不同。在生态恢复案例中,成功的生态恢复效果往往都基于长期的研究经验和积累[5]。因为准确和正确的评估草地植被演变必须基于长期的监测结果,这样才能对生物多样性,植被生态功能给予详细评估,使制定的管理方案更可靠[8]。从欧美开始,较长期的草地恢复生态学研究工作很早就得到重视和实施[9-12]。在长期生态学研究中,一般界定长期的时间范围是 20—50a 间,或者更长时间[13-14]。没有长期恢复经验积累,不可能获得很好的恢复效果,其结果很可能适得其反。突出考虑生态恢复的长期性特征,更能警示我们政策制定者,慎重考虑政策对环境影响。更多的了解不同年限的生态恢复研究案例,可为我国目前大量的生态恢复工程提供借鉴,实现扬长避短、查漏补缺;还可以为客观评估我国生态恢复工程提供参考。本文从调研的国内外 149 个退化草地恢复研究案例出发,对退化草地生态恢复的时间期限,方法,效果,及研究年限规律进行综合分析,以期给我们当前退化草地生态恢复提供借鉴价值。

1 退化草地生态恢复研究的时间、效果及分布

1.1 时间范围

当代生态学研究已经突破传统生态学研究范畴,从时间跨度之广就能看出来。Jackson [15]认为生态学研究中的时间问题,分 real time、Q-time (quaternary)和 deep-time;第一个是一般的生态学研究时间范围,从几周到几十年范围内,主要包括竞争,捕食等;第二个是从 100 年到 1 万年之间,包括演替、迁移、稳定性,保护和灭绝等;第三个范围超过 1 万年,是古生物学,进化,地理变化范畴的研究。根据这个划分,恢复生态学,特别是

草地恢复生态学一般属于 real time 时间范畴,即大多数在几十年范围内,也少有案例超过 100a。与森林相比,退化草地得到恢复的时间相对较短,因此大多草地生态学研究时间跨度也较短。

虽然,长期生态学研究的时间界定一般认为是 20—50a 之间[13-14]。与时间尺度有关的退化草地生态恢复研究案例主要侧重于对恢复技术实施后的监测,根据监测结果来评判恢复效果。根据 ISI Web of Science 数据库中,随机获取的 149 个关于草地恢复的研究案例中,大多数的时间尺度都小于 10a,也就是大多数案例根据较短期的时间研究结果来评估退化草地恢复(图 1)。其次的时间尺度在 10—20a 之内也较多,这些案例主要集中于较长期的连续监测(图 1)。恢复生态学中,长期性研究手段主要有 3 个,第一是相同样地的长期连续性监测(long-term);第二是多年代序列样地(chronosequence)的比较性分析;第三个是间断性研究样地的重访研究。在大于 20 多年的研究案例中,多数是关于退化草地恢复后,通过再访途径获得评估,一般是根据案例的文献或者资料记载来进行试验地重访 (revisiting)(图 1)。

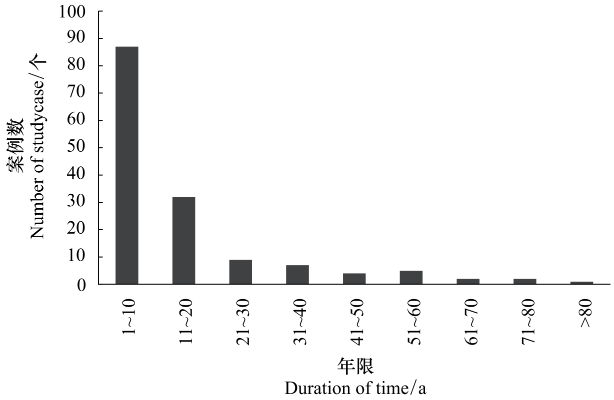

图 1 随机调查的 149 个草地恢复研究案例在不同年限段的数量分布

Fig.1 The numbers pattern in different period (years) of 149 study cases of degraded grassland restoration

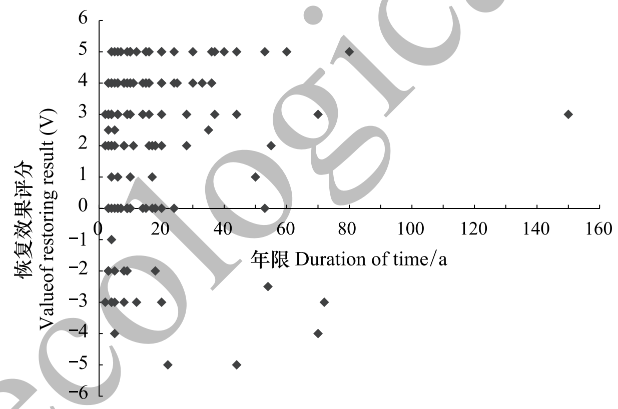

图 2 随机调查的 149 个退化草地恢复案例的恢复效果

Fig.2 Evaluation of restoring effect for 149 grassland restoration cases

1.2 恢复的效果

在对 149 个草地恢复研究案例的综合比较中,根据恢复目标和最终达到的效果进行了人为评分,评分从-5到+5,代表恢复技术实施后负作用和正作用的程度。从统计结果看(图 2),恢复结果与恢复年限并没有关系,短期和长期的恢复结果都有好有坏。说明了适宜的恢复技术与恢复时间相适应的重要性。总体来看,大于 5a 的生态恢复效果都较好,年限越长草地恢复越趋于向良性方向演替。对于恢复技术而言,退化草地的恢复尽量采用排除干扰的方法,一般都能达到很好的效果,其结果的显著性决定于年限长短[16-19]。这也提示我们,目前在我国实施的各种退化草地恢复技术短期内的效果评估难以代表对技术真实评价,需要长期跟踪及再评估,才能获得对生态恢复作用的深入认识。

不同草地类型、恢复技术,以及对不同观测对象产生的结果差别较大。在产生负结果的案例中主要集中于目标物种/群落结构的恢复[20-21]、土壤功能或氮水平的恢复[10,22],无机碳[23]。植被覆盖度降低的案例中集中于 8—9a 期限中[24]。而较长期土壤系统恢复(72a)一般都很难达到目标,这与气候环境变动有关[10]。相对而言,在草地生他系统中,针对生物多样性和植被覆盖度,一般适宜的恢复技术都能实现[11, 25-31]。而强干扰的措施一般都或多或少的在某个方面偏离预期目标,如放牧[29-30],火烧[25],施肥[32],耕作[10, 33],刈割[34]。从植被类型来看,沙化草地、干旱草地,在采取恢复措施后都能体现出正的恢复效应[35-40],但是对于草甸、湿地草地,海边草地而言,其结果较不确定[20-21, 34,36, 41-44,]。总体而言,物种丰富度较高,土壤水、养分异质性较高的草地变化不确定较高,并且难以预测。

1.3 研究案例在全球分布及年限格局

退化草地恢复长期性研究案例年限与研究地区、国家的科研能力有很大关系（图 3）。欧洲研究基础设施较完善，并且拥有较多的长期性研究定位工作站，因此现有的报道中欧洲在不同年限都有很多案例，并且伴随着时间的推移这些案例都将成为较长年限案例。美洲主要集中在美国、加拿大的研究，近些年的长期性研究快速发展，并且随着美国长期性生态学研究计划的实施，会更加加强。亚洲关于草地恢复的研究主要分布在中国，混合了长期性定位研究和多次重访案例，以及多年代比较性工作，近些年随着中国科研投入的增加逐渐得到丰富和完善。澳洲和非洲的案例相对较少，但是澳洲退化草地恢复长期性工作坚持较好，而且研究内容也非常丰富，值得我们借鉴。

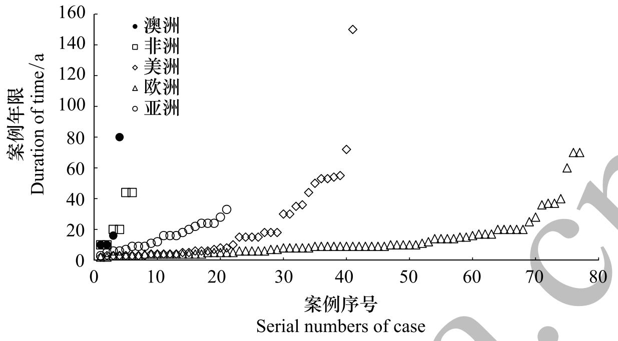

图 3　调研案例全球分布（澳洲，非洲，美洲，欧洲和亚洲）**及年限格局**

Fig.3　All 149 study cases′ pattern in different continents (Australia, Africa, America, Europe and Asia) **and periods** (years)

2　长期性退化草地生态恢复的目标和措施

2.1 恢复目标

退化草地生态恢复目标与其他生态系统恢复目标都相似，都集中于两种功能，即生态功能、生产功能，但在具体研究案例中，有较详细的区分[5]。在随机调研的 149 个案例中，生物多样性（29.48%）、植被覆盖度（24.28%）、土壤碳库（13.87%）3 个恢复目标占大多数，其余恢复目标，如生产力，昆虫群落，土壤微生物，土壤氮库，目标物种，植物群落结构，土壤种子库，土壤湿度，饲用牧草等都相对较少（图 4）。实际案例中更多的是多个目标的恢复，例如植被覆盖度和生产力[45-47]，生物多样性与生产力[48]，在案例中很少有单一的恢复目标。很多研究中，恢复目标或多或少与研究对象生态生物学特点和研究者擅长领域相关，例如土壤种子库、群落结构稳定性等，而植被覆盖度永远是恒定的指标，在各年限研究案例都存在。

调查的研究案例中，在恢复年限与恢复目标中没有一致的规律性。在欧美国家的案例中，更多是关于生物多样性，他们认为生物多样性如果能够恢复的话，那么其他诸如生产力，目标物种，土壤养分等功能都能随之恢复，这种思想实际上一直主导着当前生态恢复理论与实践[5, 49-50]。而在生物多样性恢复的实践中，当前更侧重于生态系统的管理[38,46, 51-52]。调查的研究案例中，生物多样性恢复研究年限在长期生态研究中较多，例如在澳大利亚，研究开垦的草地在弃耕后生物多样性恢复达到 80a[53]。北美斯泰普草地弃耕监测多样性达 50 多年[54]，欧洲控制实验中 N 素对草本植物多样性恢复影响能监测 70a[21]。事实上大多数长期生态恢复案例主要依靠的是定期或者不定期的监测。

比较而言，生产力恢复的研究案例一般时间都比较短，这说明长期生态学研究中生态功能是首要的。生产力功能在一定时期内受人类需求影响较大，暂时性特点较明显。调查的研究案例中，关于生产力的案例都是少于 5a 的研究[46-48,55]，只有来自中国的一个案例监测了 24a 后草地恢复的生产力[33]。事实上我国目前正在综合各种长期性监测研究对生态恢复的长期性效果、规律，进行更大范围的总结，争取给全球提供更多参考。草地恢复中将土壤系统作为恢复考察对象基本上都在短、中、长期年限都有，因此生态恢复始终将土壤系统视为关键[10, 22, 28,37, 44,56-60]。

在以前的草地生态恢复研究案例中土壤微生物关注较少，随着土壤微生物研究技术的发展，近些年关注较多[37, 40, 59, 61]。但是土壤微生物系统较为复杂，而且其恢复目标难以把握，在生态恢复中可能作为参考指标，况且与土壤养分紧密相关，一般与土壤养分一起作为整体考虑[37, 59]。作为近些年发展起来的综合分析方法，现代统计学（例如多元统计、数量分析、结构方程模型等）为植被-土壤养分-土壤微生物的关联分析提供了

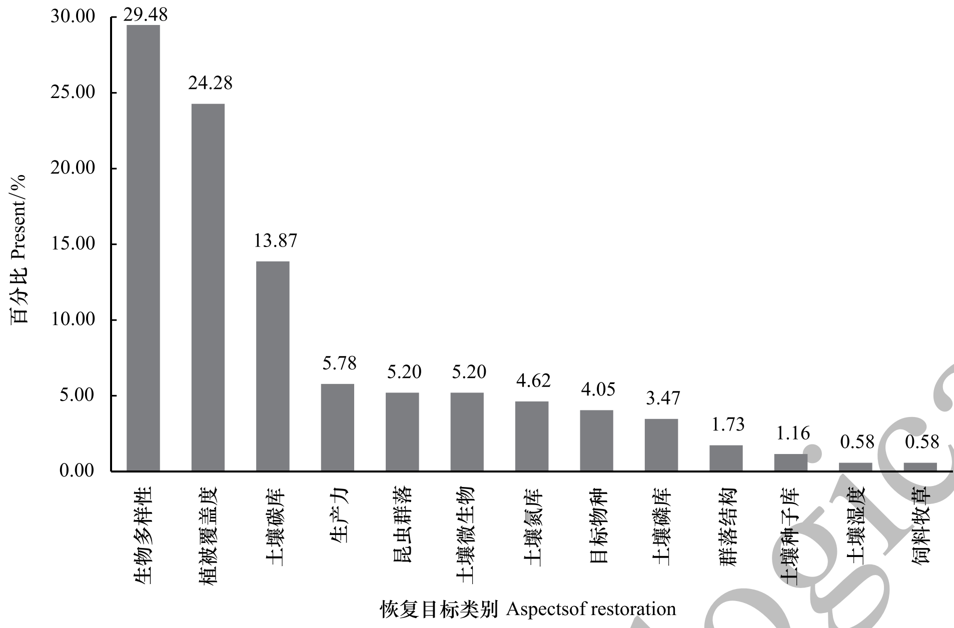

图 4 随机调查的 149 个退化草地生态恢复不同目标占案例总数的百分比

Fig.4 The ratio (%) of each restoring role in all grassland restoration cases (149)

手段,因此越来越多的生态恢复中土壤微生物成为热点目标。

有两篇研究涉及到了蚂蚁[39]、蝴蝶[61]在草地生态恢复中的情况,这两篇报告针对不同草地类型,不同恢复技术,是草地生态恢复中考虑动物,特别是昆虫的典型案例。其中 Menke 在 2015 年的研究涉及了蚂蚁群落在普列里,萨王纳草地在封育恢复的短期(3a),中长期(5—15a),以及大于 15a 的变化,很显然年限长的恢复对蚂蚁群落恢复更有利[39]。关于蝴蝶的报告中,Woodrock 等人在 2012 年的报道中研究了草地开垦后采用人工播种恢复,以及退化草地(灌丛化)清除灌丛等方法对蝴蝶的影响,其中弃耕人工播种对蝴蝶的恢复效果表现好些,这个研究年限是 10a[61]。还有一个关于昆虫群落的研究案例时间较长,前后间隔了 40a,Schuch 等人在 2011 年报告了德国东部干草原在控制木本方式下昆虫群落恢复情况,并且效果很好[62]。

2.2 恢复措施

生态恢复技术一直是恢复生态工作者的重要研究方向,然而迄今为止,难以找到很通用的恢复技术。对于退化生态系统而言,最通用的途径就是消除干扰,但是有时候消除干扰后漫长的恢复时间,确实是人们难以坚持,不得不寻求在景观、生态功能方面更加快速的恢复技术。就退化草地生态系统而言,更多恢复技术集中于土壤-植物界面,因为草地植被层片相对简单。从调查的 149 个研究案例可以看出,这些案例基本上涵盖了地球上关于退化草地恢复的主要技术(图 5)。其中应用最多的技术是人工补播或播种[36,46,55,59,63-69,],围栏禁牧(或禁止干扰)[11,18, 28,37,39,66,70-71,],放牧利用[24,29-30,36,42,72-74],刈割[41,75-80],施肥[20,32,77,81- 83]等技术。在澳大利亚火烧是常用的措施[25, 35],其他的技术如灌丛清除[61, 84],翻耕[33, 38],表土移植[44],木本防除[62],干草覆盖[85],增加 CO_2[86],增水[26]等措施带有很强的区域性,应用不是很广泛。

调查的案例中,围栏封育、人工播种,以及弃耕的恢复技术,有较多的长期研究案例[11,28, 53-54,59],其中对开垦草原的弃耕恢复研究是当前的热点内容,这对在自然状态下草原演替、草原群落建成等生态学重要性有关。调查的研究案例中火烧措施持续的时间都比较长,例如美国的林地草地火烧恢复研究持续了 4a[87],美国高羊茅草地火烧恢复研究持续了 5a[88],美国对林木入侵的草地恢复使用火烧恢复的研究持续了 7a[89];澳大利亚南澳草地火烧技术恢复研究则持续了 10a[25],瑞典干草原的火烧恢复研究持续了 15a[35]。欧洲由于牧业利用需要,很多草地恢复技术集中在如何从草地上清除扩张或侵入的灌木、林木,大多时候这种措施与放牧相结合[30],或者与人工播种结合[61]。

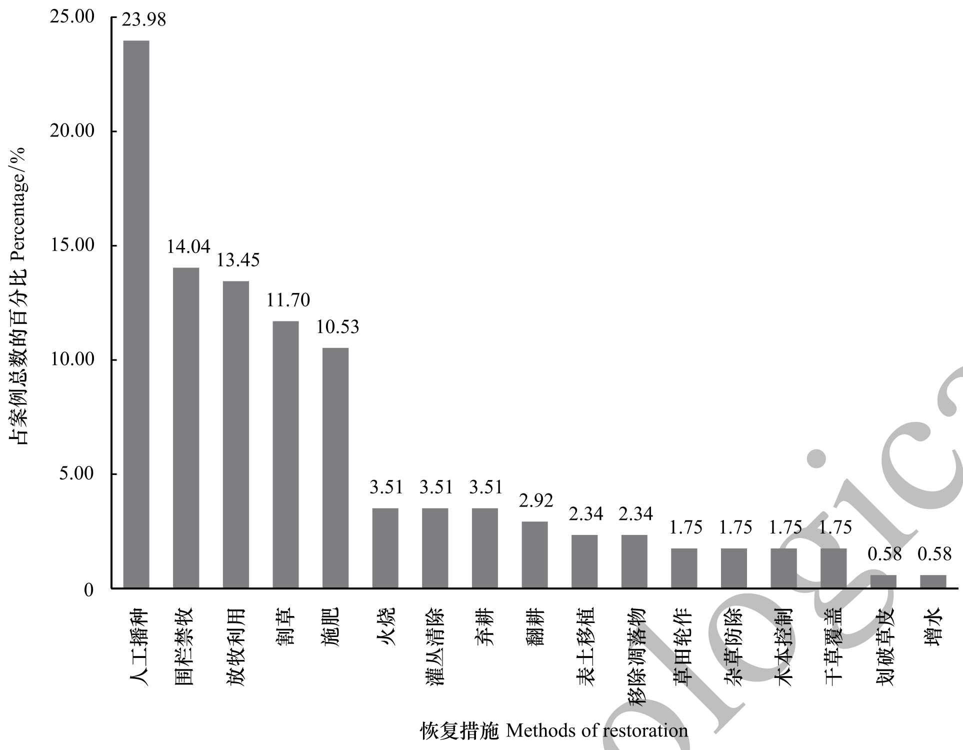

图 5　随机调查的 149 个退化草地生态恢复不同恢复技术措施占案例总数的百分比

Fig.5　The ratio (%) of each restoring technique in all grassland restoration cases (149)

在这些草地恢复技术中,值得注意的是人工播种(或人工种草)的技术应用。这种技术一般在欧美国家是用来较快速的恢复草地生态功能,且采用本地的乡土植物种子。同时一个非常重要的问题是,在已经报道的欧美国家草地恢复中使用人工播种,一般都是混合播种,并且混播的物种都在 10 多种,甚至 20、30 种,很少有像我们国家采用的 1 种、2—3 种、4—5 种这样少的混播技术应用到草地生态恢复中[36,51,58-59,64,66,68,90]。在美国内布拉斯加州一个草地人工种植恢复研究中,研究人员认为 15 种的混播是低物种数的混播,同时他们采用了 95 种物种种子的混播作为高丰富度混播材料,这项研究用来分析人工混播群落的稳定性和恢复能力[47]。但是,在我国人工播种恢复退化草地,采用混播草地植物物种非常少,甚至有时只有一种[91]。从生态学原理上,几种草种混播做草地生态恢复应该禁止,这样会导致人工种植草地极其不稳定,且造成再次退化,以致恢复工作投入的人力物力大量被浪费。这也是我国草地人工恢复又迅速退化的一个非常重要原因[92]。

3　退化草地生态恢复研究获得长期数据和结果的途径

3.1　连续监测方法

在我们调查的 149 个研究案例中,其中涉及到连续监测方法的有 66 个(表 1)。很显然,连续监测对长期生态学研究十分重要,这对于研究的可信度,和更加清楚的认识生态系统变化十分有用,但是这依赖于大量的人力、物力投入[33,109]。对退化草地生态恢复而言,连续的监测有助于展示详细恢复过程和提出更有效的管理措施。连续监测面临最大的挑战是长期资助项目,可持续的研究团队和经费支撑,这在全球都是十分困难的。随着自动化设备的发展,连续的监测已经变得越来越容易实现了。短期的研究很多能够实现连续监测,特别是每年或者每个月的观测研究[41,55, 84]。越来越多的自动化设备、遥感、气象监测等方法被应用到连续的监测中。

完全采用连续监测方法主要集中在短期的研究中,一般小于 10a [30,43,47,55,84,94-96];也有长于 10a 的连续监测研究,这种研究除了依靠较稳定的研究队伍,经费资助外[16,26, 110],也依靠国家的持续监测工程,例如中国内

蒙古一项研究连续持续了 24a[33]。

连续监测或者调查方法也出现在定期、不定期重访过程中。诸如对以前研究地点,案例隔多少年以后重新再研究,那么可能在此期间开展连续 2、3a 或者更长时间研究,来验证前期研究产生的结果(表 1)。例如,Fritch 等人[18],对于爱尔兰集约化农业利用的草地恢复过程中的研究,7a 前恢复措施,在 7a 后连续开展了 2a 的调查。Matějková 等人[24] 对于希腊山地草地放牧恢复的 8a 研究中,其中后 4a 采用了连续调查方法。Maccherini 等人[36] 在意大利对于钙化草地恢复研究持续了 9a,但是由于中间某种原因中断了,其研究在开始和后来都采用了连续调查监测的方法。Sykora 等人[107] 在荷兰 14a 间的研究也是中间间隔了一段时间又重启研究。Munson 和 Lauenroth [91] 在对美国半干旱草地研究,持续了 18a,但是采用了不定期重新调查方法,每次调查都坚持 2—3a 的连续研究。Pavlu 等人[80] 在德国草地研究持续了 20a,只有中间一段时间连续了 4a 调查工作。更长期的对比工作,例如 Van Eekeren 等人[111] 在比利时草田轮作时间跨度 36a,Bakker 等人[108] 在北美间隔了 50a,他们的工作都是很久以后重新连续调查。

表 1 研究案例中实地调查重复方法、年限及文献来源

Table 1 Different field survey repeating methods of all cases (149) and their duration years, reference

方式 Field survey repeating methods	年限(案例数) Years (case number)	案例的文献来源 References
每年连续 Every year of continuous	2(3), 3(10), 4(7), 5(6), 6(5), 10(2), 11(1), 24(3)	[16, 20, 26, 30, 33, 38, 41, 43, 46-48, 51, 55, 64, 69, 75, 78, 82, 84, 93-96]
定期重访 Revisiting at regular intervals	4(2), 14(2), 17(3)	[32, 57, 87]
不定期重访 Revisiting aperiodically	3(7), 4(2), 5(2), 6(5), 7(1), 8 (6), 9 (8), 10 (8), 12(2), 15(4), 16 (4), 18 (4), 20 (5), 22 (1), 25 (1), 28(8), 30 (2), 33(1), 35 (1), 36 (1), 37(2), 40 (1), 44(3), 53 (2), 54 (1), 55(1), 60 (1), 70(2), 80(1), 150(1), >15 (2), 3—5(4), 5—15(2)	[10-11, 19, 21-23, 25, 27-29, 31, 35, 37, 39, 40, 42, 44-45, 53-56, 58-63, 66-67, 71, 73-74, 76-77, 81, 83, 85, 87, 91, 97-105]
每年连续+不定期重访 Every year+revisiting aperiodically	5(1), 11(1), 16(16), 20(1)	[12, 77, 88, 106]
每年连续+不定期重访+每年连续 Every year+revisiting aperiodically+ Every year	14(1), 20(1)	[80, 107]
每年连续+中断+每年连续 Every year+break off+every year	9(6)	[36]
不定期重访+定期重访 Revisiting aperiodically+Revisiting at regular intervals	28(1)	[79]
不定期重访+每年连续+定期重访 Revisiting aperiodically + every year + revisiting at regular intervals	14(1)	[72]
不定期重访+每年连续 Revisiting aperiodically+every year	5(1), 7(3), 8(1), 9(1), 20(1), 36(1), 50(1)	[18, 24, 65, 72, 78, 108, 111]

3.2 定期重访式方法

实验案例的重访研究是获得生态恢复效果可靠性评估的有效有段。事实上,就研究的时间特点,连续调查也属于定期重访,在这里定期重访,特指一项研究持续进行,但至少间隔时间以年为单位,进行有规律的重新研究。在我们调查的 149 个研究案例中,这种严格定期重访的案例不多,仅有 7 项(表 1),可见定期重访的方法应用不是很广泛。的确这需要很长远研究计划,和更为持续的人力、物力支撑。在我们调查 7 个案例中,共出现了 3 个研究报道,分别是 Halpern 等人研究美国草地清除林木的影响,每隔两年重复调查[87];在石楠灌

从草地研究工作,每隔 3—4a 定期重复调查,一共持续了 17a[57];在英国集约化农业利用草地恢复研究中每隔 2a 重复一次调查,一共持续了 14a[32]。Schrautzer[79]在德国湖边草地研究案例也采用了定期重访方法,持续了 28a,是在多年后重新在原来一个实验地点重新调查了 10a,在这 10a 内每隔 2—3a 调查一次。

3.3 不定期重访方法

在草地生态恢复中,大多年限较长的研究工作更多的依赖于不定期重复方法[19, 31,35, 37, 61, 83]。我们调查的案例中除了每年连续监测案例,和定期重复案例,其余都与不定期重复方法有关,更有 82 个案例是典型的不定期重复的研究工作(表 1)。很显然,不定期重复方法更符合当前生态恢复研究工作的特点和人类认识、人力/物力支撑现状,相对而言信息量也较大。不仅在发达国家,这种方法应用广泛,而且在更多发展中国家和地区,随着社会稳定,科学研究工作的兴起,这种方法也得到了更多推广和应用[28, 37, 59]。在我们调查的案例中,不定期重访集中在大于 5a 的研究案例中,也很多 10a 以上的研究案例(表 1)。而混合了连续监测的不定期重访的研究案例更多的是 10a 以上的案例。

不定期重访方法在草地恢复研究中,从低成本、信息量、研究意义、可对比性等方面来说,非常值得推广。事实上在草地恢复在演替过程中,连续监测有时候非属必要,毕竟自然演替,尤其在植被较稳定阶段,短期难以反映出变化。更长年限的研究,如果想得到持续性结果,也只能通过不定期重访方法,毕竟一代人、两代人获得可持续的研究支持十分有限。例如 Gardner[11]研究新墨西哥荒漠草地间隔了 30a;Kinucan 和 Smeins[97]研究德克萨斯草地间隔了 36a 进行重访;Hejcman 等人[83]在捷克的研究间隔了 37a 重访;Bakker 等人[108]再次重访并连续监测相同样地间隔了 50a;Coffin 等人[54]在北美重访了 53a 前的斯泰普草地研究样地;White 等人[10]根据资料重访了 54a 前和 72a 前的滨州草地样地。这些长时间跨度的研究都得到了很有意义的结果,对一个地区植被、管理都有很好的借鉴意义。较长时间跨度的不定期重访研究有一个特别要注意的事情,就是以前研究资料的可寻性,也就是必须能够借助原来的资料能够准确的找到原来地点,并且较详细资料记载,否则其研究对比性难以把握。在有定位实验站条件的区域容易实现,当然在现在信息技术发展条件下,这样的研究也比较容易实现。

3.4 基于大数据的时间序列的建立与分析

大数据分析的可靠性在于大量数据的统计趋势性分析,基本上在草地恢复生态学研究中,一种是整合分析(Meta-analysis)的大数据统计,另外一种是实地测量的大数据统计分析。大数据的时间序列分析,也必须建立在某种,或者各种实验调查基础上。特别是对各种相似、相同方法研究的整合分析。现在比较流行的 meta 分析方法,也很多是案例挖掘,采用研究结果的无量纲化后统一对比分析。在生态学领域,meta 技术招致大量的批评,导致很多单纯的数据挖掘者,而非实验主义者[112-113]。在这里我们更推荐实地的 meta 技术,也就是亲自采用同一种方法调查,然后综合对比分析。加拿大汤普森河大学大学(Thompson Rivers University)Fraser Lauchlan 教授提出的"分散-协作-统一"的大数据整合的研究途径(Coordinated distributed experiments)来获取更多的生态数据,这种方法具有方法统一性,跨区域性等特点,是目前生态学大数据网络研究的典范[114]。

长期性研究时间序列建立,或者进行大数据综合分析实际上更多依赖于田野的不定期重访。在案例统计中,我们根据实际情况将其作为不定期重复部分(表 1),但在讨论中,我们单独分开讨论,目的是能够将其特殊价值体现出来。更多的综合对比工作,借助于对很多研究样地重访后建立长期年代序列(chronosequence),进行对比分析[21, 40, 53, 56, 59, 60, 99]。Carilla 和 Grau[101]的研究比较特殊,他们采用第三方年代(树轮)确定方法来研究草地演变,但其信息不确定性也较大。

4 总结和展望

通过上述对文献报道的 149 个研究案例分析,我们确定长期性退化草地生态恢复研究确实对科学研究和生态恢复实践具有重要价值,受限于人力、物力的支持,且依赖于多方面,方法至关重要。因此,借助于案例重

访方法获得可比较的长期性数据,以及在生态恢复中长期性年代序列数据库方法值得推荐和加强,可以很好获得长期性研究结果。恢复方法与恢复年限之间没有必然联系,更取决于恢复方法的适宜性。特别注意,在我国采用植物种子种植恢复退化草地的工作,应该注重更多的物种数混合种植技术,而非我们当前的仅采用几种植物物种混合方法。当前,我国已经大范围的开展了生态恢复研究工作,并且建立了各种研究基地,以便于开展综合性,长期性研究工作,特别需要能够持续的研究设计和资助体系。因此,当前的短期实地研究工作,尽可能的实现连续性的观测研究,这样为后来的长期性研究能够提供更多的数据参考。从学科范畴来讲,恢复生态学更需要新的范式来引领理论和技术的发展[115-116]。

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